

Evolutions of Neutron Stars and their Magnetic Fields.

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Abstract

Estimations of magnetic fields of neutron stars, observed as radio and X-ray pulsars, are discussed. It is shown, that theoretical and observational values for different types of radiopulsars are in good correspondence. Radiopulsars in close binaries and millisecond pulsars, which have passed the stage of disk accretion (recycled radiopulsars), have magnetic fields 2-4 orders of magnitude smaller than ordinary single pulsars. Most probably, the magnetic field of the neutron star was screened by the infalling material. Several screening models are considered. Formation of single recycled pulsars losing its companion is discussed. Magnetic fields of some X-ray pulsars are estimated from the cyclotron line energy. In the case of Her X-1 this estimation exceeds considerably the value of its magnetic field obtained from long term observational data related to the beam structure evolution. Another interpretation of the cyclotron feature, based on the relativistic dipole radiation mechanism, could remove this discrepancy. Observational data about soft gamma repeaters and their interpretation as magnetars are critically analyzed.

1 Introduction

First theoretical estimations of neutron star magnetic fields have been obtained from the condition of the magnetic flux conservation during contraction of a normal star to a neutron star [36]:

$$B_{ns} = B_s \left(\frac{R_s}{R_{ns}} \right)^2. \quad (1)$$

For main sequence stellar magnetic field $B_s = 10 \div 100$ Gs, and stellar radius $R_s = (3 \div 10)R_\odot \approx (2 \div 7)10^{11}$ cm, we get $B_{ns} \approx 4 \times 10^{11} \div 5 \times 10^{13}$ Gs, for a neutron star radius $R_{ns} = 10^6$ cm. As shown below, this simple estimation occurs to be in a good correspondence with most observational data.

Neutron stars are born with magnetic fields comparable with the fields of youngest pulsars. The youngest and the best studied Crab pulsar PSR 0531+21

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is about 1000 years old and has a magnetic field about $3.5 \cdot 10^{12}$ Gs. The pulsar in Vela PSR 0833-45 is 10 times older, but has almost the same magnetic field. Magnetic fields of some oldest pulsars PSR 0826-34 ($3 \cdot 10^7$ years old) and PSR 1819-22 ($3 \cdot 10^7$ years old) are equal to $1.4 \cdot 10^{12}$ and $1.1 \cdot 10^{12}$ Gs respectively [63]. The simple comparison of these data gives the indication to low, or may be negligible, damping of the magnetic field due to Ohmic losses inside the neutron star matter. This conclusion seems to be plausible, because in very dense strongly degenerate layers of the neutron star, where the electrical current, producing magnetic fields could flow, the electrical conductivity is enormously high, so in this case we may expect practically no Ohmic damping. These simple estimations had been confirmed by the detailed statistical analysis of the big sample of single radiopulsars [7], where the conclusion about low (or negligible) Ohmic damping of magnetic fields of radiopulsars was obtained quite reliably.

2 Radio pulsars

It is now commonly accepted that radio pulsars are rotating neutron stars with inclined magnetic axes. For rotating with angular velocity Ω dipole, the rotational energy losses [56, 82] are determined as $\dot{E} = AB^2\Omega^4$. The rotational energy is $E = \frac{1}{2}I\Omega^2$, I is an inertia momentum of the neutron star. By measuring of $P = 2\pi/\Omega$ and \dot{P} , we obtain the observational estimation of the neutron star magnetic field as

$$B^2 = \frac{IP\dot{P}}{4\pi^2 A}. \quad (2)$$

It was shown by [38] that energy losses by a pulsar relativistic wind are important also when the magnetic and rotational axes coincide, and one may use (2) with $A = \frac{R_{ns}^6}{6c^3}$, and B_{ns} corresponding to the magnetic pole, at any inclination angle. Magnetic fields of radio pulsars estimated using (2) with observational values of P and \dot{P} lay in a wide region between 10^8 and 10^{13} Gs [61]. There are two distinctly different groups: single radiopulsars with periods exceeding 0.033 sec, and magnetic fields between 10^{11} and 10^{13} Gs, and recycled pulsars (RP), present or former members of close binary systems with millisecond periods and low magnetic fields between 10^8 and 10^{10} Gs. Low magnetic field of recycled pulsars is probably a result of its damping during preceding accretion stage [19, 21].

3 Recycled radiopulsars

During several years after discovery of pulsars only single objects had been found. It was an impression, that pulsars avoid binaries. When half (or even more) stars are binaries, this phenomena was explained either by pair disruption during supernova explosion leading to pulsar formation, or by absence of SN explosions at the end of evolution of stars in close binaries [96].

Detailed analysis of the fate of close X-ray binaries in low-mass systems, namely Her X-1, was done in [19], and the conclusion was made that evolution of such system will be ended by formation of a non-accreting neutron star in close binary, which should become a radio pulsar. It was shown, that neutron star rotation is accelerated during disk accretion stage, so the second time born (recycled) radio pulsar should become visible, provided it has a magnetic field similar to other single pulsars. Absence of radio pulsars in close binaries, in spite of intensive searches could be explained by the only reason: during accretion stage the magnetic field of the neutron star is screened by the inflowing accreting gas, so the recycled pulsar should have $B \sim 10^8 - 10^{10}$ Gs, 2-4 orders of magnitude smaller than average field strength of radio pulsars. Discovery of the first binary pulsar [43], and subsequent discovery of more than 50 recycled pulsars [58, 62] had confirmed this conclusion: all recycled pulsars have small values of magnetic fields, as was predicted in [19].

A simple estimation of the magnetic field screening during accretion had shown a large potential possibility of such process. It was estimated in [12] that in absence of instabilities leading to penetration of the infalling plasma into pulsar magnetosphere, the pressure of the accreting gas exceeds the magnetic pressure of the dipole with $B = 10^{12}$ Gs. already after one day of accretion at subcritical accretion rate $10^{-9} M_{\odot}/\text{year}$, and the original magnetic dipole is completely buried under a plasma layer, and currents in the plasma prevent external appearance of stellar magnetic field. In reality the instability and gas penetration through the magnetosphere make the screening process much slower, and when the penetration layer reaches the surface of the star the external magnetic field strength of the neutron star could reach the stationary state.

From the statistical analysis of 24 binary radio pulsars with nearly circular orbits and low mass companions, it was discovered [99] a clear correlation between spin period P_p and orbital period P_{orb} , as well as between the magnetic field and orbital period: pulsar period and magnetic field strength increases with the orbital period at $P_{orb} > 100$ days, and scatters around $P_p \sim 3$ ms and $B \sim 2 \cdot 10^8$ Gs for smaller binary periods. These relations strongly suggest that an increase in the amount of accreted mass leads to a decay of the magnetic field, and a 'bottom' field strength of about 10^8 G is also implied. Several models of magnetic field screening during accretion had been considered, see [26, 27] and references therein. Evolutionary aspects of formation of recycled pulsars are discussed in [19, 98], and summarized in [6]. Several scenarios had been analyzed in [19, 98] for the evolution of binaries, massive enough to produce the neutron star or black hole in one or both remnants. During the evolution such stars go through stages of different nuclear burning, which are ended by formation of carbon-oxygen white dwarf, or proceeds until formation of the iron - peak elements core, which collapses with formation of the neutron star or a black hole. The first born relativistic star (neutron, or black hole) goes through the stage of an accreting binary X-ray source, and the evolution of such system is finished after end of evolution of the second component, and the end of accretion. During the evolution of massive close binary there are possibilities of a disruption of the binary after the first or the second collapse,

which may be accompanied by explosion with large mass ejection, or by a kick due to anisotropy in a mass ejection or in neutrino flux. It was nevertheless concluded in [19], that "evolutionary analysis cannot exclude formation of close binary, containing neutron star, and another star on the last evolutionary state (white dwarf, neutron star, black hole). Contrary, this analysis indicates to formation of such binaries at the end of evolution of sufficiently massive systems with a large probability." Same conclusion was obtained in [98]. The absence of discovery of binary pulsars in 1973 was unambiguously explained in [19] as follows: "The absence of radiopulsars in close binaries may be explained if we suggest additionally, that magnetic field of the neutron star is damped during accretion stage"

The probabilistic conclusion about formation of radiopulsars in close binaries was definitely confirmed in [19] by the analysis of the evolution of one of the best learned X-ray pulsars Her X-1. The component of the neutron star in this system is a low mass star which will end its life by formation of the white dwarf, when the pair cannot be disrupted. On the other hand, during accretion the neutron star acquires a rapid rotation, and it was shown in [19], that during the process of termination of accretion the neutron star - X-ray pulsar cannot follow the stationary period, increasing with decreasing of the accretion rate \dot{M} , and after the end of accretion will remain to be rather rapidly rotating neutron star with a period of the order, or smaller than periods of the known radiopulsars. So, the only explanation of absence of binary radiopulsars in 1973 year remains their faintness, connected with low magnetic field.

The first proof of this conclusion came soon by discovery of the first binary radiopulsar PSR 1913+16 [43]. This pulsar was a rapidly rotating with a period 0.059 s in the close binary with a period 7^h45^m . Just after the discovery I have identified this object with the old recycled pulsar with low magnetic field [11]. Measurements [95] of the period derivative \dot{P} , which gave possibility to estimate the age of this pulsar $\tau = \frac{P}{2\dot{P}} \approx 10^8$ years, and magnetic field $B \approx 2 \cdot 10^{10}$ Gs had proofed this identification. Among more than 100 recycled pulsars most objects consist of a neutron star with low mass white dwarf companion, and the systems with two neutron stars, like in PSR 1913+16 are in minority. Double-neutron-star (DNS) binaries are rare, and only six such systems are known. All recycled pulsars, with white dwarf or neutron star companions, have magnetic fields $10^8 - 10^{10}$, so the hypothesis about field damping on the accretion stage seems to be correct.

Another convincing evidence in favor of magnetic field graving during accretion appeared by discovery of the first binary system, containing two radiopulsars. The recently discovered 23-ms pulsar J0737–3039A was found to be in a 2.4-hr eccentric orbit with another compact object that the observed orbital parameters suggested was another neutron star [24]. The 2.8-sec pulsar J0737–3039B was discovered [62] as the companion to the pulsar J0737–3039A in a highly-relativistic double-neutron-star system, allowing unprecedented tests of fundamental gravitational physics. The short orbital period and compactness of the system and the high timing precision made possible by the large flux density and narrow pulse features of this pulsar promise to make this system a

superb laboratory for the investigation of relativistic astrophysics. The resulting in-spiral will end in coalescence of the two stars in about 85 My. This discovery significantly increases the estimates of the detection rate of DNS inspirals by gravitational wave detectors [24]. The clock-like properties of pulsars moving in the gravitational fields of their unseen neutron-star companions have allowed unique tests of general relativity and provided evidence for gravitational radiation.

The properties of these pulsars fit very well the evolutionary scheme of formation of binary pulsars from [19]. According to this scheme the 23 ms pulsar had accelerated its rotation during accretion, when its magnetic field was decreased due to screening of the accreting material. The second 2.8 s pulsar was born later in SN explosion, which did not disrupt the pair. Therefore, ms pulsar should be older, and have weaker magnetic field. Indeed, 23 ms pulsar has $B = 6.3 \times 10^9$ Gs, and characteristic age $\tau = 210$ My; and 2.8 s pulsar has $B = 1.6 \times 10^{12}$ Gs, and $\tau = 50$ My [62]. The masses of neutron stars in this binary are estimated as $1.34 M_\odot$ for 23 ms, and $1.25 M_\odot$ for 2.8 s pulsars.

3.1 Magnetic field damping during accretion

Accretion induced Ohmic heating and dissipation have been investigated in many works (see i.g. references in [29]). This mechanism may work only if the magnetic field is produced by electrical current in the outer layers of the accreting neutron star, which may be heated during accretion. Evidently, the highly degenerate neutron star core is not sensible to this heating and will preserve its very high conductivity. Therefore magnetic field, originated by deep inside electrical currents may become weaker only due to screening by the infalling plasma during accretion [19]. Different models of magnetic field screening during accretion have been considered. It is usually accepted that matter is channelized by the dipole magnetic field and flows to the magnetic poles of the neutron star [18, 2]. As the magnetic field of the neutron star decreases because of the screening due to accreting material, it is less able to channelize the accretion flow and thereby the polar cap widens. One can easily find out how the angular width θ_P of the polar cap depends on the surface magnetic field B_s of the neutron star (see, for example, [89]). The field line starting from θ_P at the surface of the neutron star, with a radius r_s , is the last closed field line of the dipolar field and passes through the Alfvén radius r_A . It easily follows that

$$\sin \theta_P = \left(\frac{r_s}{r_A} \right)^{1/2}. \quad (3)$$

Assuming that the ram pressure of the freely in-falling accreting material at the Alfvén radius equals the magnetic pressure, a few steps of easy algebra give

$$r_A = (2GM)^{-1/7} r_s^{12/7} B_s^{4/7} \dot{M}^{-2/7}, \quad (4)$$

where M is the mass of the neutron star and \dot{M} the accretion rate. It follows from (3) and (4) that

$$\sin \theta_P \propto B_s^{-2/7}. \quad (5)$$

This is how the polar cap widens with the weakening magnetic field until θ_P becomes equal to 90° when (5) obviously ceases to hold. On taking $M = 10^{33}$ gm, $\dot{M} = 10^{-8} M_\odot \text{ yr}^{-1}$, $r_s = 10$ km, $B_s = 10^{12}$ G, we find from (4) that $r_A \approx 300$ km. Substituting this in (3), we conclude that the initial polar cap angle is of order 10° .

The accreting materials falling through the two polar caps flow horizontally towards the equator in both the hemispheres. At the equator, the opposing materials flowing in from the two poles meet, sink underneath the surface (inducing a counter-flow underneath the equator-ward flow at the surface) and eventually settle radially on the neutron star core. With a suitably specified flow having these characteristics, it was studied kinematically in [54, 30] how the magnetic field evolves with time, taking into account the fact that the polar cap width changes with the evolution of the magnetic field, thereby altering the velocity field also. It was found in the simulations [30] that the equator-ward flow near the surface is quite efficient in burying the magnetic field underneath the surface. However, when the polar cap opens to 90° , the accretion becomes spherical and radial. It is found that such accretion is not efficient in burying the magnetic field any further. The magnetic field at the surface of the neutron star keeps decreasing until the polar cap opens to 90° , after which the magnetic field is essentially frozen, since the radial accretion cannot screen it any further. If $\theta_{P,i}$ is the initial polar cap width, then it follows from (5) that the magnetic field would decrease by a factor $(\sin 90^\circ / \sin \theta_{P,i})^{7/2}$ from its initial value before it is frozen to an asymptotic value. On taking $\theta_{P,i}$ in the range 5° – 10° , this factor turns out to be about 10^3 – 10^4 , exactly the factor by which the magnetic fields of millisecond pulsars are weaker compared to the magnetic fields of ordinary pulsars.

Put another way, the magnetic field freezes when the Alfvén radius becomes equal to the neutron star radius. The asymptotic value of the surface magnetic field can be found directly from (4) by setting r_A equal to r_s , which gives

$$B_{\text{asympt}} = (2GM)^{1/4} \dot{M}^{1/2} r_s^{-5/4}. \quad (6)$$

On using the various standard values mentioned before, we find $B_{\text{asympt}} \approx 10^8$ G. When the magnetic field falls to this value, it can no longer channelize the accretion flow, resulting in the flow becoming isotropic. Such a flow is unable to screen the magnetic field any further. After the accretion phase is over, the neutron star appears as a millisecond pulsar with this magnetic field. This could be the reason why millisecond pulsars are found with magnetic fields of order 10^8 G. Note that the accretion flow in the polar region of a magnetized neutron star is sensitive to various magneto-hydrodynamic instabilities and it is difficult to make an assessment of the effectiveness of screening without a full three-dimensional computation which is yet to be attempted.

A simple analytical model of the magnetic field screening in incompressible fluid approximation was considered in [26, 27]. It was found a very rapid decrease of the magnetic field in the polar cap during a time scale $\tau_p \approx 10^5 \dot{M} (m_B / 10^{-3} M_\odot)$ years, where $m_B = (B_{\text{asympt}} / B_0)^{4/7} M_{cr}$ with B_{asympt} from (6), initial magnetic field of the neutron star B_0 , and mass of the crust $M_{cr} = 0.03 M_{\text{odot}}$. Here the polar magnetic field is tending to the same asymptotic value (6), and development of instabilities should decrease also the equatorial magnetic field to similar values.

It was noted in [21], that "magnetic fields buried during intensive accretion may start to "percolate" outside after the end of accretion", what could increase the magnetic field of recycled pulsars with time, see also [75]. Some estimations of the field percolation outside have been done in [79]. The authors considered cases with very rapid field increase due to percolation during $10^3 - 10^4$ years, up to the initial value which the neutron star had before the start of accretion. Evidently, this conclusion is in contradiction with observation, because all recycled pulsars which could be very old, even up to 10^{10} years [58], have equally small magnetic fields. This contradiction is connected with the artificial model considered in [79], where the percolation was started from the depth not more than 260 m, corresponding to the accreted material less than $5 \cdot 10^{-5} M_\odot$. The conductivity in the outer crust of the neutron star could be small enough to permit such a rapid percolation. Actually, during the accretion phase lasting $10^7 - 10^8$ years the amount of the accreted material is much larger, the magnetic field is buried to much deeper layers with much higher conductivity. Therefore the outward percolation of the magnetic field in the recycled pulsars should be negligible.

3.2 Formation of single recycled pulsars: Enhanced Evaporation

Among the pulsars, which can be attributed to the recycled (rapid rotation + low magnetic field) there are many single objects. The mechanism of the pair disruption and formation of a single RP is not quite clear. After discovery of the first eclipsed radiopulsar it was suggested that the companion could be evaporated [51], but statistical properties did not confirm it. The concentration of the recycled pulsars (RP) to the globular clusters (GC), 47 RP from the total number 103 are situated in GC [58], is very similar to the distribution of low mass X-ray binaries (LMXB). Taking into account, that presently the total relative mass of GC in Galaxy is about 10^{-3} and about one half of LMXB are situated in GC, the relative concentration of LMXB in GC is 1000 larger than in the Galaxy [92]. The similarity of distributions of LMXB and RP may be considered as another evidence to their genetic relation [19, 21, 85]. According to [58] there are 21 single RP in GC (45%), and only 9 single RP in the galactic bulge (16%). This evident statistical difference indicates that not only birth of LMXB, but also the disruption of the binaries are connected with close stellar encounters, which are much more frequent in GC than in the bulge [13]. It was suggested in [13], that single RP in the bulge could be the remnants of

the completely evaporated GC, same origin may have also LMXB of the bulge [23]. Numerical simulations made in [84] have shown that only pairs with large orbital periods 10 – 100 days could be destroyed by close stellar encounters in globular clusters. However, it follows from observations [58], that RP are usually members of more close binaries. The solution of this problem may be done by the mechanism of "Enhanced Evaporation" (EE), suggested in [14].

It was shown theoretically in [40] and confirmed later by numerical experiments [1], that stellar encounters of stars with close binaries lead to energy extraction from the binary and heating of the cluster field stars. Contrary to that, collisions with sufficiently wide binary lead to its father widening, and finally to its destruction. This property is interpreted very easily. The kinetic energy exchange between stars during encounter is determined by their velocities, almost independently on their single or binary origin. Relaxation processes in stellar encounters lead to establishing of equipartition of energies of all stars. It means, that star with larger kinetic energy lose it, and the one with smaller energy gain it. For single stars it would lead to real equipartition, so that stars with larger energies in average loose it, but contrary result takes place if one of the encountering objects is a close binary. In close binary star is rapidly rotating on the orbit. If this rotational energy exceeds the average energy of stars in the cluster there is an average energy transfer to the field stars. When the star in the binary loose its kinetic energy, its orbit is changing in such a way that it starts to rotate faster than before, and the pair becomes tighter. The binary has an effective negative heat capacity, connected with the validity of the virial theorem [56] in the binary system. The net loose of the energy by the pair leads to acceleration of the orbital motion. When tight binaries are formed in the GC, they could destroy it during time less than the cosmological one, so the LMXB and single RP in the bulge could be formed in such a way.

The situation is quite different, when one of the degenerate members in the close binary fills its Roche Lobe. Let isolated binary contain a neutron star with a mass M_1 , and a degenerate dwarf with a mass M_d . When the dwarf fills its Roche lobe, the radius of the dwarf R_d is connected with a distance between stellar mass centers R_{12} by a relation

$$R_d = R_{12} \frac{2}{3^{4/3}} \left(\frac{M_d}{M} \right)^{1/3}, \quad M = M_1 + M_d. \quad (7)$$

For white dwarfs with an equation of state valid in small mass dwarfs the equilibrium models had been constructed in [107]. The radius of a degenerate dwarf increases with decreasing of its mass until very low masses, when repulsion effects may change this dependence. Gravitation radiation leads to loss of the angular momentum of the system, and tries to make the binary closer, but approach of the dwarf to the neutron star induces a mass transfer. If we suggest that the dwarf fills its Roche lobe, which radius coincides with the dwarf radius, than due to mass transfer dwarf mass decreases, its radius increases with the Roche lobe radius, and the binary is becoming softer. Evolution of such binary under the action of a gravitational radiation was calculated in [14]. It

was obtained that during a cosmological time $\tau_c = 2 \cdot 10^{10}$ years the mass of the carbon dwarf reaches $0.0025M_\odot$. At that time the period of the binary P reaches about 1.5 hours,

$$P = \frac{2\pi R_{12}^{3/2}}{(GM)^{1/2}} = \frac{9\pi R_d^{3/2}}{\sqrt{2GM_d}}, \quad (8)$$

and the dwarf velocity in the binary

$$v_d = \frac{2\pi R_{12}}{P} = \frac{\sqrt{2}}{3^{2/3}} \left(\frac{GM^{2/3}M_d^{1/3}}{R_d} \right)^{1/2}, \quad \text{at } M_d \ll M. \quad (9)$$

The pair becomes soft, and would be destroyed by close encounters with the field stars when the kinetic energy of the dwarf in the binary is less than the average kinetic energy of the field stars: $M_f v_f^2 > M_d v_d^2$. For globular clusters 47 Tuc and ω Cen the corresponding velocities are 10.3 and 16.8 km/s, and masses are equal to $0.67M_\odot$ and $0.51M_\odot$ respectively. According to calculations [14], the pair in these GC is becoming soft, when the dwarf mass becomes less than $6 \cdot 10^{-4}$ and $9 \cdot 10^{-4}$ respectively. These masses are several times less than the dwarf mass after cosmological time, and to reach these masses one needs about 10 cosmological times.

It was shown in [14], that stellar encounters of the field stars with "hard" pairs, when the binary loose its energy and momentum, act similar to the gravitational radiation. They make the hard pair even harder, but when the dwarf in the pair fills its Roche lobe such encounters make the pair softer. When the encounters with the field stars are effective enough they may transform the hard binary in the state of the mass exchange into the soft one, which would be destroyed directly by close encounters. This process was called in [14] as "enhanced evaporation". For the estimation of the momentum relaxation time τ_m we use the expression [93], which is valid for stars with comparable masses, because in the close binary the centrum mass motion may take the extra momentum

$$\tau_m = \frac{v_d^3}{4\pi G^2 M_f^2 n_f \Lambda}. \quad (10)$$

Here Coulomb logarithm $\Lambda \approx 10$, n_f is the average density of the field stars. With account of (9) the characteristic encounter time, which determines the time of the pair destruction due to EE is written as

$$\tau_m \approx 10^{22} \frac{mm_d}{m_f^2 n_{51}} \text{ c}. \quad (11)$$

Here small m determine masses in solar units, $n_{51} = n_f / 10^{-51} \text{ cm}^{-3}$. The approximate relation for dwarf mass - radius relation is used, which is valid for the ideal fermi gas stars, $R = 7.6 \cdot 10^8 m_d^{1/3}$. Everywhere carbon dwarfs with $\mu_e = 2$ are considered, μ_e is the number of baryons per one electron. Following the evolution of the pair due to encounters it was found in [14] that in order to destroy the binary due to EE process the field star density should exceed

$$n > 3 \cdot 10^5 \frac{m^{9/11}}{m_f^2} \text{pc}^{-3}. \quad (12)$$

The central parts of the most dense GC, where single recycled pulsars are concentrated, like M15, satisfy this demand. So, EE process is probably responsible for the formation of the single RP in GC, as well as in the bulge, where they could find themselves after the evaporation of the whole GC. Note, that binaries with the hydrogen-helium brown dwarfs are destroyed easier due to EE [14], with the coefficient 2 instead of 3 in (12).

4 X-ray binaries

There are several ways to estimate observationally magnetic field of an X-ray pulsar. During accretion matter is stopped by the magnetic field at the alfvénic surface, where gaseous and magnetic pressures are in a balance. At stationary state Keplerian angular velocity of the accretion disk at the alfvénic surface is equal to the stellar angular velocity [83] $\Omega_K = \Omega_s = \Omega_A$. Otherwise neutron star would be accelerated due to absorption of matter with large angular momentum, or decelerated due to throwing away matter with additional angular momentum [49]. X-ray pulsars may have spin-up and spin-down stages [8], but most of them show average spin-up, what indicate to their angular velocity being less than the equilibrium one. This is observed in the best studied X-ray pulsar Her X-1 [90, 33]. Analysis of spin-up/down phenomena in the X-ray pulsars indicate to important role of the mass loss [59], and to stochastic origin of spin-up/down transitions [60].

For a given luminosity $L_{36} = L/(10^{36} \text{ergs/s})$ and dipole magnetic field at stellar equator $B_{12} = B/(10^{12} \text{Gs})$ we get the following value of the equilibrium period [57], for the neutron star mass $M_s = 1.4M_\odot$

$$P_{eq} \approx 2.6 B_{12}^{6/7} L_{36}^{3/7} \text{s}. \quad (13)$$

For Her X-1 parameters $L_{36} = 10$, $P = 1.24 \text{s}$, we get a magnetic field corresponding to the equilibrium rotation $B_{12}^{eq} = 0.9$. Taking into account the average spin-up of the pulsar in Her X-1, we may consider this value as an upper limit of its magnetic field. Even more rough estimations of the magnetic field in X-ray pulsars follow from the average spin-up rate under condition $\dot{J}_{rot} = \dot{M} \Omega_A$, or restrictions on the polar magnetic field value following from the observed beam structure and condition of local luminosity not exceeding the critical Eddington one. These conditions lead to smaller values of the magnetic field of Her X-1 on the level $10^9 - 10^{10} \text{Gs}$ [19, 20, 10].

Observations of low mass X-ray binaries (LMXB) indicate to very low values of their magnetic fields due to absence of X-ray pulsar phenomena. Modulation of X-ray flux permitted to reveal the rotational period of the neutron star in the LMXB SAX J1808.4-3658 corresponding to the frequency 401 Hz, due to RXTE observations (see reviews [100, 102]). This observations fill a gap and

form a long-waiting link between LBXB and recycled millisecond pulsars [85], as neutron stars with very low magnetic field (up to 10^8 Gs).

The most reliable estimation of the magnetic field of the X-pulsar Her X-1 comes from detailed observations of the beam variation in this pulsar on different stages, made on the satellites ASTRON [90], and GINGA [33] and RXTE [88]. This pulsar, in addition to 1.24 s period of the neutron star rotation, is in a binary system with an orbital period 1.7 days, and shows a 35 day cycle, where during only 12 days its luminosity is high. During other 23 days its X-ray luminosity strongly decreases, but small changes in the optical luminosity and remaining strong reflection effect indicate, that the X-ray luminosity remains almost the same during all 35 day cycle. Visible decrease of the X-ray flux is due to an occultation phenomena. The model which explains satisfactory the phenomenon of the 35 day cycle is based on the precession of the accretion disc with the 35 day period, and occultation of the X-ray beam during 23 days. Analysis of the beam structure during high and low X-ray states lead to the conclusion, that during the low state we observe not the direct X-ray flux from the neutron star, but the flux, reflected from the inner edge of the accretion disc. This conclusion is based on the 180 deg phase shift between the X-ray beams in high and low states [90, 33, 88]. In order to observe the X-ray flux reflected from the inner edge, situated near the Alfvén radius of the accretion disc, it cannot be very far away from the neutron star. The estimations give the upper limit to the ratio of the Alfvén and stellar radii

$$\frac{r_A}{r_s} \leq 20. \quad (14)$$

The schematic picture of the accretion disc and its inner edge orientation around the neutron star at different stages of the 35 day cycle is shown in Fig.1, taken from [90]. As was indicated above, the value of the Alfvén radius is determined by the neutron star mass ($M_s = 1.4M_\odot$), mass flux $\dot{M} = 3 \times 10^{16}$ g/s, corresponding to the luminosity $L = 10^{37}$ ergs/s, and the value of the magnetic field. Taking dipole radial dependence of the magnetic field $B = B_s(r_s/r)^3$, and neutron star radius $r_s = 10^6$ cm, we obtain the ratio in the form $r_A/r_s \approx 300B_{12}^{4/7}$. To have this ratio not exceeding 20 we get an inequality $B \leq 3 \times 10^{10}$ Gs.

It was found in [97] a feature in the spectrum of Her X-1 at energies between 50 and 60 keV. Interpreting it as a cyclotron line feature according to $E_X = \frac{\hbar e B}{m_e c}$ leads to the value of the magnetic field $B_{cycl} = (5 - 6) \times 10^{12}$ Gs, what is much higher than any other above mentioned estimations. Spectral features had been observed also in other X-ray sources. Recent observations on RXTE [41], and Beppo-SAX [86] of the pulsating transient 4U 0115+63 had shown a presence of 3 and 4 cyclotron harmonics features, corresponding to the magnetic field strength of 1.3×10^{12} Gs. A comparison of the shapes of the beam in cyclotron harmonics may be used for testing the nature of these features. Cyclotron features had been observed in several X-ray sources [77], and they always had corresponded to large values of magnetic fields $B_{cycl} > 10^{12}$ Gs. Such situation was not in good accordance with a well established observational fact, that all recycled pulsars, going through a stage of an X-ray source, have much smaller

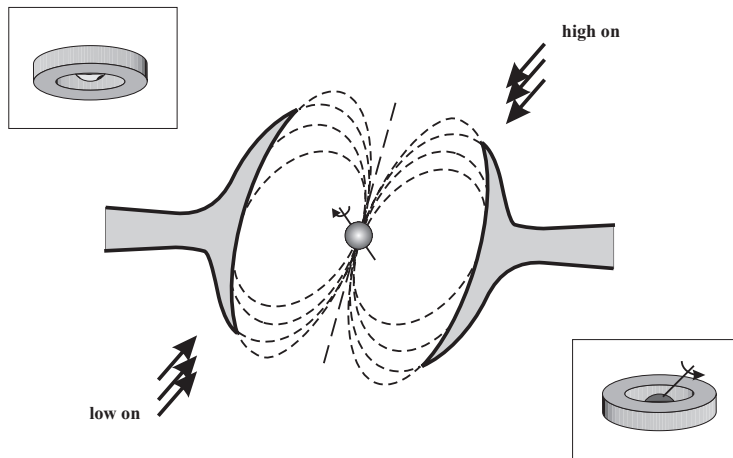


Figure 1: Configuration of the inner edge of the disk and the neutron star; neutron star and the disk in the "high-on" state (left top box), and in the "low-on" state (right bottom box).

magnetic fields, usually not exceeding 10^{10} Gs. Particularly, for the Her X-1 the value of its magnetic field, following from the cyclotron interpretation of the spectral feature, was in contradiction with all other observations, including the most reliable, based on the beam shape variability during 35 day cycle.

5 Relativistic dipole interpretation of the spectral feature in Her X-1

It seems likely that this conflict is created by using the non-relativistic formula connecting cyclotron frequency with a value of the magnetic field. According to [18], ultrarelativistic electrons with a temperature $\sim 10^{11} K$, may be formed in the non-collisional shock during accretion, emitting a relativistic dipole line. The mean energy of this line is broadened and shifted relativistically, in comparison with the cyclotron line, by a factor of $\gamma \simeq \frac{kT}{mc^2}$. The spectrum profile of the relativistic dipole line is calculated in [5] for various electron distributions, where the model of the hot spot of Her X-1 is considered, and it is shown that the overall observed X-ray spectrum (from 0.2 to 120 KeV) can arise under the fields near $5 \cdot 10^{10}$ Gs which are well below B_{cycl} , and are not in the conflict with other observations.

According to [37, 9], in the magnetic field near the pulsar the cross component of a momentum of electrons is emitting rapidly, while the parallel velocity remains constant. Hence the momentum distribution of the electrons is anisotropic $p_{\perp}^2 \ll p_{\parallel}^2$, with $p_{\perp} \ll mc$, $p_{\parallel} \gg mc$. Assume for simplicity that the transverse electron distribution is two-dimensional Maxwellian $dn =$

$$\frac{N}{T_1} \exp\left(-\frac{mu^2}{2T_1}\right) d\frac{mu^2}{2}, T_1 \ll mc^2.$$

In the relativistic dipole regime of radiation the electron is non-relativistic in the coordinate system, connected with the Larmor circle. In the laboratory system, where the electron is moving with a velocity V , the angle between the magnetic field and electron momentum vectors is smaller than the angle of the emitting beam. In this conditions we may consider that all radiation is emitted along the magnetic field with an intensity $J(0)$, after integration over du , at frequency ω_{md} as [5]

$$J(0) = \frac{2Ne^4B^2T_1}{\pi c^5 m^3 (1 - \frac{V}{c})}, \quad \omega_{md} = \omega_{cycl} \sqrt{\frac{1 + \frac{V}{c}}{1 - \frac{V}{c}}} \approx 2\omega_{cycl} \frac{E_{\parallel}}{m_e c^2}, \quad (15)$$

where $\omega_{cycl} = \frac{eB}{mc}$. That gives $1 - \frac{V}{c} = \frac{2\omega_{cycl}^2}{\omega^2}$. Let us consider the parallel momentum distribution of the electrons as: $dn = f(p_{\parallel}) dp_{\parallel}$. Substituting of dn for N and using $p_{\parallel} = \frac{mc}{2} \frac{\omega}{\omega_{cycl}}$, we obtain for the spectral density

$$J_{\omega} = \frac{e^2 T_1}{2\pi c^2 \omega_{cycl}} \omega^2 f\left(\frac{mc}{2} \frac{\omega}{\omega_{cycl}}\right) d\omega. \quad (16)$$

Let us consider two cases. The first is a relativistic Maxwell $f = \frac{n_0 c}{T_2} \exp\left(-\frac{p_{\parallel} c}{T_2}\right)$, where n_0 is a number of emitting electrons. The spectrum is

$$J_{\omega} = \frac{n_0 e^2}{2\pi c \omega_{cycl}} \frac{T_1}{T_2} \omega^2 \exp\left(-\frac{mc^2 \omega}{2\omega_{cycl} T_2}\right) d\omega. \quad (17)$$

It has a single maximum at $\frac{\omega}{\omega_{cycl}} = \frac{4T_2}{mc^2}$. In the second case we have $f = \frac{n_0}{\sqrt{\pi}\sigma} \exp\left[-\frac{(p_{\parallel} - a)^2}{\sigma^2}\right]$. The spectrum of radiation is

$$J_{\omega} = \frac{n_0 e^2 T_1}{2\pi^{3/2} c^2 \omega_{cycl} \sqrt{\sigma}} \omega^2 \exp\left(-\frac{(\frac{mc}{2} \frac{\omega}{\omega_{cycl}} - a)^2}{\sigma^2}\right) d\omega. \quad (18)$$

When $\sigma \ll a$ this spectrum has a single maximum at $\omega \simeq \frac{2a}{mc} \omega_{cycl}$. [5] had approximated experimental spectra taken from [76, 70]. The last spectrum (solid line) and its fitting (dashed line) are shown in Fig.2. It was taken in accordance with [18], $a = 7 \cdot 10^{-4} \frac{\text{eV} \cdot \text{s}}{\text{cm}}$, corresponding to average electron energy $E_{\parallel} = ac \approx 20$ MeV, and the best fit for the line shape was obtained at the magnetic field strength $B = 4 \cdot 10^{10}$ Gs. In this model the beam of the "cyclotron" feature is determined by the number distribution of the emitting relativistic electrons, moving predominantly along the magnetic field, over the polar cap.

In order to obtain the whole experimental spectrum of the Her X-1 the following model of the hot spot (Fig.3) was considered in [5]. A collisionless shock wave is generated in the accretion flow near the surface on the magnetic pole of a neutron star. In it's front the ultrarelativistic electrons are generated. Under the shock there is a hot turbulent zone with a temperature T_e , and optical

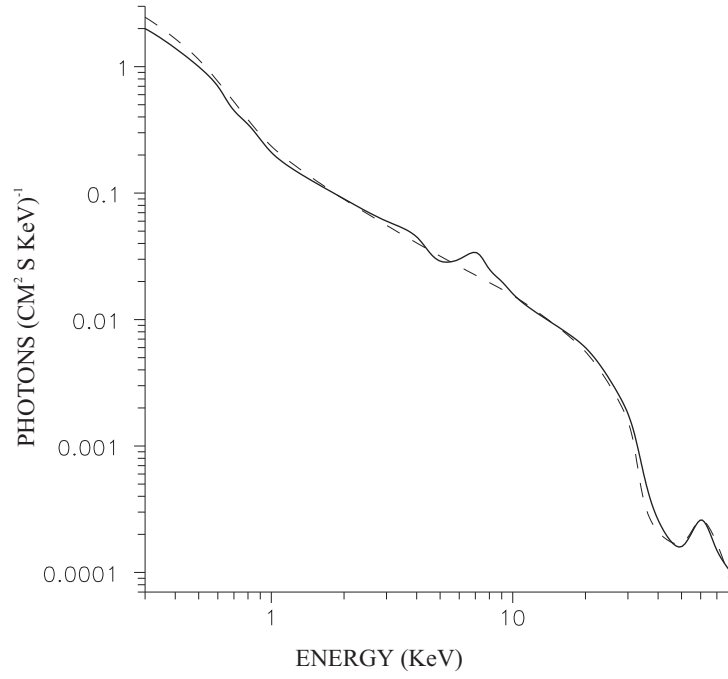


Figure 2: Comparison of the observational and computational X-ray spectra of Her X-1. The solid curve is the observational results taken from [70], the dot curve is the approximation with $T_s = 0.9$ KeV, $T_e = 8$ KeV, $\tau_e = 14$, $a = 7 \cdot 10^{-4} \frac{\text{eV} \cdot \text{s}}{\text{cm}}$, $\sigma = 10^{-4} \frac{\text{eV} \cdot \text{s}}{\text{cm}}$, $B = 4 \times 10^{10}$ Gs.

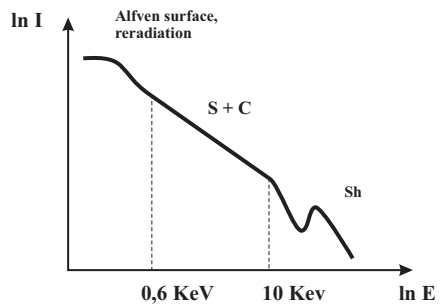
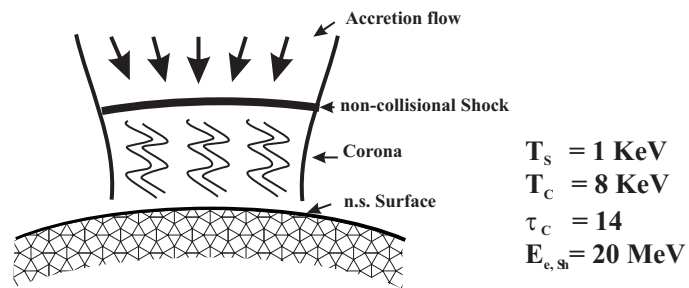


Figure 3: Schematic structure of the accretion column near the magnetic pole of the neutron star (top), and its radiation spectrum (bottom).

depth τ_e , situated over a heated spot with a smaller temperature on the surface of the neutron star.

The whole X-ray spectrum of pulsar Her X-1 from [70] is represented in Fig.3 by the solid line. There are three main regions in it: a quasi-Planckian spectrum between 0,3 and 0,6 KeV, that is generated (re-radiated) near the magnetosphere of the X-ray pulsar; power-law spectrum (0.6 ÷ 20) KeV with a rapid decrease at 20 KeV, and the "cyclotron" feature. The power-law spectrum is a result of comptonization in the corona of a black-body spectrum emitted by the stellar surface. The comptonized spectrum has been calculated according to [94]. Setting the neutron star radius equal to 10 km, distance to the X-ray pulsar 6 Kps, hot spot area $S = 2 \cdot 10^{12}$ cm², the best fit was found at $T_s = 1$ KeV, $T_e = 8$ KeV, $\tau_e = 14$, which is represented in Fig.3 by the dashed line.

The observations of the variability of the "cyclotron" lines are reported by [77]. Ginga detected the changes of the cyclotron energies in 4 pulsars. The change is as much as 40 % in the case of 4U 0115+63. Larger luminosity of the source corresponds to smaller average energy of the cyclotron feature. These changes might be easily explained in our model. The velocity of the accretion flow decreases with increasing of the pulsar luminosity because locally the luminosity is close to the Eddington limit. As a result the shock wave intensity drops as well as the energy of the ultrarelativistic electrons in it's front, leading to decrease of the relativistic dipole line energy.

6 Cyclotron harmonics in the X-ray pulsars

Reports about discoveries of several cyclotron harmonics in spectra of several X-ray pulsars appeared according to observations from RXTE and BeppoSAX: X0115+63 [101]; Vela X-1 [55, 80]; 4U1907+09 [31, 32]; A0535+26 [50] There are at least 3 harmonics observed in the spectrum of X0115+63 [42, 86]. This is the most reliable source with the cyclotron harmonics. Other sources are less reliable, the second harmonic there is very weak. These observations are very important and could help in solving some problems of the theory of spectra formation in the X-ray pulsars. There is still an open question, are the cyclotron features in the spectra of X-ray pulsars of absorption or emission origin. In the paper [4] all lines in 4 above mentioned sources are interpreted as emission features.

It is not clear what kind of momentum distribution have electrons radiating the cyclotron lines. It is needed, that the motion of electrons across the magnetic field would be subrelativistic (or nonrelativistic), because otherwise many harmonics would merge, forming continuum synchrotron spectrum. In most cases only one first harmonic is visible. It is accepted usually that the speed of electrons along the magnetic field is considerably less than the light speed c . However, it is possible, like in the case of Her X-1, that the momentum distribution of the electrons is highly anisotropic, so that their speed is subrelativistic across the magnetic field, and ultrarelativistic along it. Analysis of different observational data of the X ray pulsar Her X-1 had shown that all

data can be explained without contradictions under suggestion that the electrons forming the cyclotron feature are ultrarelativistic with very anisotropic momentum distribution.

When the perpendicular electron energy is high enough for emission of several cyclotron harmonics, the resulting spectrum of magneto-dipole radiation, produced by electrons with nonrelativistic perpendicular and ultrarelativistic parallel momentum distribution, has a very specific form [4]. Note that the perpendicular energy is measured in the frame of the Larmor circle, and the parallel energy is measured in the laboratory frame of the observer. Different harmonics in the spectrum of magneto-dipole radiation become nonequidistant in the laboratory frame. It could permit in principle to determine are there electrons with the ultrarelativistic parallel energy by analyzing the shape of the lines. The number of photons of n -th harmonic, averaged over the time, which the emitted by the star in the unit of time, in the unit of the body angle, in the unit frequency interval is determined by the formula [4]

$$Q_n = \alpha \rho R^2 \frac{n^{2n}}{n!} \left(2 \frac{\tilde{\omega}}{n} - \left(\frac{\tilde{\omega}}{n} \right)^2 \right)^{n-1} \left(1 + \left(\frac{\tilde{\omega}}{n} - 1 \right)^2 \right) \left(\frac{T}{2m_e c^2} \right)^n, \quad (19)$$

where R is the stellar radius, ρ is the surface density of the electrons, α is the fine structure constant, and non-dimensional frequency is defined as

$$\tilde{\omega} = \frac{\omega}{\gamma \omega_H} \quad (20)$$

The frequency $\tilde{\omega}$ of the n -th harmonic covers the interval $1/\gamma \leq \tilde{\omega} \leq 2n$, so the relation (19) is valid only in this frequency interval, and Q_n is zero outside it. Combining several harmonics together we obtain the final spectrum of the magneto-dipole radiation. The observed lines in the spectrum of X0115+63[86] are non-equidistant when they are interpreted as emission lines. Besides, they are very broad as indicated in the Fig.6 from [86]. It is shown in [4], that magneto-dipole radiation of electrons with very anisotropic momentum distribution could be the most natural explanation of such spectrum. The calculated spectrum of magneto-dipole radiation corresponding to the perpendicular electron temperature 20 is represented in Fig.5 from [4]. Note that the shape of this spectrum does not depend on the parallel relativistic factor γ_{\parallel} , all frequencies are proportional to the same factor γ_{\parallel} . We need to know the parallel relativistic factor γ_{\parallel} for determination of the stellar magnetic field. This factor is depending on the physical conditions in the accretion flow and may be different for different X-ray pulsars.

7 Magnetars

Among more than 2000 cosmic gamma ray bursts (GRB) 4 recurrent sources had been discovered, and were related to a separate class of GRB, called soft gamma

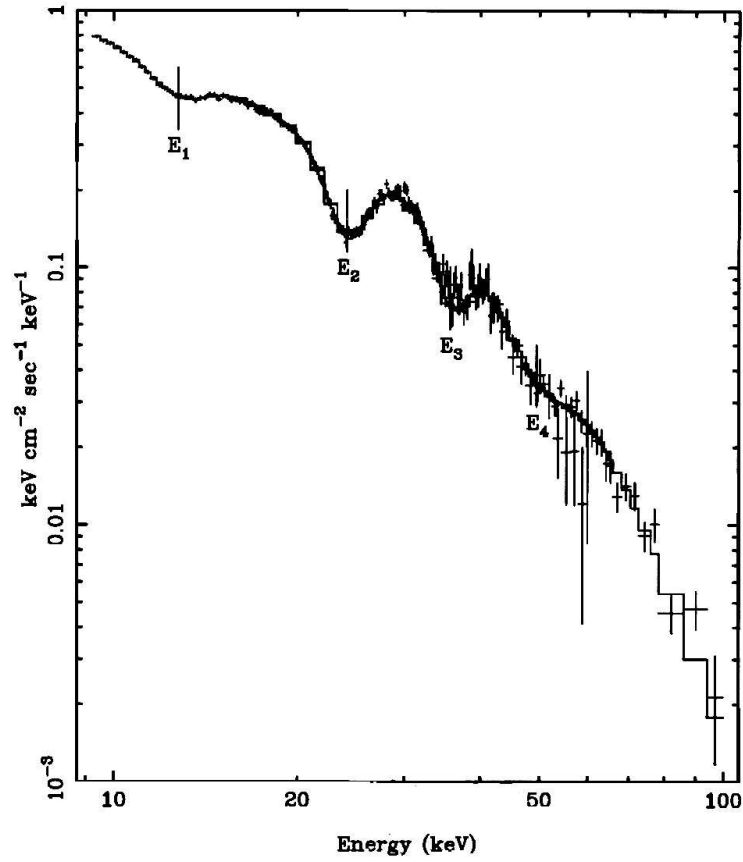


Figure 4: Observational spectrum of the main pulse of the X-ray pulsar X0115+63 in hard part of the spectrum with harmonics, according to observation by BeppoSAX, from [86]

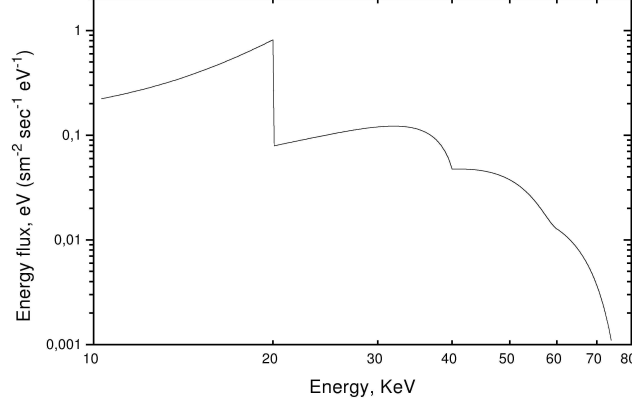


Figure 5: Theoretical spectrum of 4 harmonics of magneto-dipole radiation calculated according (19), for the perpendicular temperature $T_{\perp} = 20$. The non-dimensional energy is given along the x - axis in a linear scale, and the emitted energy along the y axis is given in the logarithmic scale, from [4].

repeaters (SGR). Besides observations of short, soft, faint recurrent bursts, three of them had given giant bursts, most powerful among all GRB. All four SGR are situated close or inside SNR, three of them show long periodic pulsations. These properties had separated SGR, situated in our or nearby galaxies, in a quite special class, very different from other GRB, which are believed to have a cosmological origin at red shifts $z \sim 1$. One SGR 1627-41 had been discovered by BATSE [103] and three other had been discovered in KONUS experiment in 1979 [65, 66, 39]. Three of SGR show regular pulsations, and for two of them \dot{P} had been estimated, indicating to very high values of the magnetic fields, up to 10^{15} Gs, and small age of these objects. SGR have the following properties [35], [44]-[48], [52, 53, 65], [67]-[69], [78, 104].

1. SGR0526-66 [65, 69].

It was discovered due to a giant burst of 5 March 1979, projected to the edge of the SNR N49 in LMC. Accepting the distance 55 kpc to LMC, the peak luminosity in the region $E_{\gamma} > 30$ keV is equal to $L_p = 3.6 \times 10^{45}$ ergs/s, the total energy release in the peak $Q_p = 1.6 \times 10^{44}$ ergs, in the subsequent tail $Q_t = 3.6 \times 10^{44}$ ergs. The short recurrent bursts have peak luminosities in this region $L_p^{rec} = 3 \times 10^{41} - 3 \times 10^{42}$ ergs/s, and energy release $Q^{rec} = 5 \times 10^{40} - 7 \times 10^{42}$ ergs. The tail was observed about 3 minutes and had regular pulsations with the period $P \approx 8$ s. There was not a chance to measure \dot{P} in this object.

2. SGR1900+14 [67, 69, 53, 104].

It was discovered first due to its recurrent bursts, the giant burst was observed 27 August, 1998. The source lies close to the less than 10^4 year old SNR G42.8+0.6, situated at distance ~ 10 kpc. Pulsations had been observed in the giant burst, as well as in the X-ray emission observed in this source in quiescence by RXTE and ASCA. \dot{P} was measured, being strongly variable. Accepting the distance 10 kpc, this source had in the region $E_\gamma > 15$ keV: $L_p > 3.7 \times 10^{44}$ ergs/s, $Q_p > 6.8 \times 10^{43}$ ergs, $Q_t = 5.2 \times 10^{43}$ ergs, $L_p^{rec} = 2 \times 10^{40} - 4 \times 10^{41}$ ergs/s, $Q^{rec} = 2 \times 10^{39} - 6 \times 10^{41}$ ergs, $P = 5.16$ s, $\dot{P} = 5 \times 10^{-11} - 1.5 \times 10^{-10}$ s/s. This source was discovered at frequency 111 MHz as a faint, $L_r^{max} = 50$ mJy, radiopulsar [91] with the same P and variable \dot{P} good corresponding to X-ray and gamma-ray observations. These values of P and average \dot{P} correspond to the rate of a loss of rotational energy $\dot{E}_{rot} = 3.5 \times 10^{34}$ ergs/s, and magnetic field $B = 8 \times 10^{14}$ Gs. The age of the pulsar estimated as $\tau_p = P/2\dot{P} = 700$ years is much less than the estimated age of the close nearby SNR. Note that the X-ray luminosity of this object $L_x = 2 \times 10^{35} - 2 \times 10^{36}$ ergs/s is much higher, than rate of a loss of rotational energy, what means that rotation cannot be a source of energy in these objects. It was suggested that the main source of energy comes from a magnetic field annihilation, and such objects had been called as magnetars [34].

3. SGR1806-20 [52, 48].

This source was observed only by recurrent bursts. Connection with the Galactic radio SNR G10.0-03 was found. The source has a small but significant displacement from that of the non-thermal core of this SNR. The distance to SNR is estimated as 14.5 kpc. The X-ray source observed by ASCA and RXTE in this object shows regular pulsations with a period $P = 7.47$ s, and average $\dot{P} = 8.3 \times 10^{-11}$ s/s. As in the previous case, it leads to the pulsar age $\tau_p \sim 1500$ years, much smaller than the age of SNR, estimated by 10^4 years. These values of P and \dot{P} correspond to $B = 8 \times 10^{14}$ Gs. \dot{P} is not constant, uniform set of observations by RXTE gave much smaller and less definite value $\dot{P} = 2.8(1.4) \times 10^{-11}$ s/s, the value in brackets gives 1σ error. The peak luminosity in the burst reaches $L_p^{rec} \sim 10^{41}$ ergs/s in the region 25-60 keV, the X-ray luminosity in 2-10 keV band is $L_x \approx 2 \times 10^{35}$ ergs/s is also much higher than the rate of the loss of rotational energy (for average \dot{P}) $\dot{E}_{rot} \approx 10^{33}$ ergs/s.

4. SRG1627-41 [67, 103].

Here the giant burst was observed 18 June 1998, in addition to numerous soft recurrent bursts. Its position coincides with the SNR G337.0-0.1, assuming 5.8 kpc distance. Some evidences was obtained for a possible periodicity of 6.7 s, but giant burst does not show any periodic signal [67], contrary to two other giant burst in SGR. The following characteristics had been observed with a time resolution 2 ms at photon energy $E_\gamma > 15$ keV: $L_p \sim 8 \times 10^{43}$ ergs/s, $Q_p \sim 3 \times 10^{42}$ ergs, no tail of the giant burst had been observed. $L_p^{rec} = 4 \times 10^{40} - 4 \times 10^{41}$ ergs/s, $Q^{rec} = 10^{39} - 3 \times 10^{40}$ ergs. Periodicity in this source is not certain, so there is no \dot{P} .

To measure \dot{P} the peaks of the beam are compared during long period of time. Both SRG with measured \dot{P} have highly variable beam shapes, what implies systematic errors in the result. Another source of systematic error comes from the barycenter correction of the arriving signal in the source with an essential error in angular coordinates. This effect is especially significant for determination of \dot{P} [22], but when observational shifts are short the error in the coordinates could not be extracted easily. Earth motion around the Sun, as well as the satellite motion around the Earth may influence the results. Nevertheless, independent measurements of P and \dot{P} in such different spectral bands as radio and X-rays gave similar results for SGR1900+14.

The physical connection between SGR and related SNR is not perfectly established: SNR ages are much larger, than ages of SNR estimated by P and \dot{P} measurements, and all four SGR are situated at the very edge of the corresponding SNR, or well outside them. Using the pulsar age estimation we come to conclusion of a very high speed of the neutron star at several thousands km/s, exceeding strongly all measured speeds of radiopulsars. Physical properties of the pulsars observed in SGR are very unusual. If the connection with SNR is real, and the distances to SGR are the same then the pulsar luminosity during giant bursts is much larger than the critical Eddington luminosity. As follows from simple physical reasons, when the radiation force is much larger than the force of gravity, the matter would be expelled at large speed, forming strong outflow and dense envelope around the neutron star which could screen pulsations. No outflowing envelope around SGR have been found. The large difference between \dot{E}_{rot} and average $L_x + L_\gamma$ luminosity needs to suggest a source of energy, much larger than the one coming from the rotational losses. It is suggested that in "magnetars" the energy comes from the magnetic field annihilation [34]. It is rather surprising to observe the field annihilation without formation of relativistic particles, where considerable part of the released energy should go. Radio emitting nebula should be formed around the SGR, but had not been found. So, it is not possible to exclude that there is no physical connection between SNR and SGR, that SGR are much closer objects, their pulsar luminosity is less than the Eddington one, and their magnetic fields are not so extremely high.

There is a striking similarity between SGR and special class of X-ray pulsars called anomalous X-ray pulsars (AXP). Both have periods in the interval 6 - 12 seconds, binarity was not found, spin-down of the pulsar corresponding to small age ~ 1000 years, observed irregularities in \dot{P} (see e.g. [73]). The main difference is an absence of any visible bursts in AXP, characteristic for SGR. Suggestions had been made about their common origin as "magnetars" [52, 73]. Other models of AXP had been discussed (see e.g. [74]). We may expect that establishing of the nature of AXP would help strongly for the determination of the nature of SGR.

8 Discussion

Interpretation of SGR as "magnetars", and the hypothesis about the magnetic field annihilation as the main source of energy arises questions, when we compare this model with the well established astronomical data. The giant explosions in GRB produce huge amount of energy, $> 10^{44}$ ergs in gamma region, and comparable amount in relativistic particles, generated during the field annihilation. 6 orders of magnitude lower energy output in the form of relativistic particles, produced during starquakes in the Crab pulsar make a visible changes in the morphology of the Crab nebula [87]. There are no data indicating the changes in the SNR structure after any giant burst of GRB, while it should be possible to observe the results of such a production of such a huge amount of energy in a short time. Magnetic field annihilation is accompanied by a particle acceleration, so SGR should become a bright radio source, at least after the giant burst. Nevertheless, SGRs are very faint radio sources, and do not show increase of radio emission during giant bursts.

Comparison of giant bursts in SGR and short GRB (duration less than 2 seconds) shows a big resemblance of both events. They have similar length, structure and spectra, which are harder than spectra of long GRB ([28]). If SGR would be about 10 times more distant objects we could see only their giant bursts, which undoubtedly would be interpreted as short GRB. The galaxies of our local group, containing SGR would be observed as sources of short GRB. Having in mind, that Andromeda galaxy is about 3 times heavier than the Galaxy [3], we should expect about 10 SGR which could produce a comparable number of giant bursts during the observational time (~ 30 years), visible as short GRB [15, 16, 17]. Analysis of BATSE and KONUS catalogs does not give any evidence about GRBs coinciding with any Local Group galaxy, including Andromeda [66, 81] Better statistical estimation and search in BATSE/KONUS data are desirable for investigation of connection between short GRB and SGR.

The present interpretation of SGR suggests a neutron star with very high magnetic field, which is very short living, and should not be visible in its present view after about 1000 years. During this time the neutron star will not have time to cool enough, so it will be visible at least as soft X-ray source with a temperature $> 3 \cdot 10^5$ K during about 10^5 years [105]. It would be interesting to look for such remnants in the existing and future X-ray surveys. No candidates for such remnants are found until now. In total we could expect about 10^8 neutron stars as remnants of SGR [17], and about 1000 of them should have surface temperatures exceeding $> 3 \cdot 10^5$ K.

Mechanism of "magnetar" emission in SGR suggests magnetic field annihilation as the main source of the energy. We will not discuss the physics of such process, which looks out very strangely, because it is unclear how it is possible to annihilate the field, which is produced by electrical currents deep inside the neutron star, in its core, or at least in its crust. Let us consider the results of such annihilation. Solar flashes produced by field annihilation are characterized by very broad spectrum, from radio to gamma. It remains unclear how it is possible to provide γ -radiation by magnetic field annihilation without appearance

of large number of ultra-relativistic particles and strong nonthermal emission in other spectral bands.

The estimation of the magnetic fields of "magnetars" in SGR is done using the usual formula (refref2), which gives estimation of the magnetic fields in rotationally powered pulsars. In the situation, when $L_{tot} \gg \dot{E}_{rot}$ the decrease of the rotational period may be connected not only with the dipole-like radiation, leading to (refref2), but may be much more effective due to ejection of relativistic particles (pulsar wind) induced by the field annihilation. It will lead to much smaller values of the estimations of the SGR ages, which are too small in comparison with the corresponding SNR ages even with this artificial interpretation. As was indicated in [64] there are no reasons to use (2) with the measured P and \dot{P} for estimations of SGR ages.

Contrary to SGR and AXP the age and magnetic field estimations of radiopulsars do not have such contradictions and seems quite reliable. During last few years several radiopulsars have been discovered, which have very similar periods and magnetic fields, but otherwise behave like ordinary pulsars. The first discovery of 8.5 s pulsar J2144-3933 with a normal magnetic field $B = 2.0 \cdot 10^{12}$ Gs, and large characteristic age $\tau = 2.8 \cdot 10^8$ years was reported in [106]. The period of this pulsar is well inside the interval 6-12 s, characteristic for AXP, but magnetic field and age are similar to the majority of radiopulsars. Farther discoveries revealed existence of radiopulsars with very high fields, subscribed to "magnetars". Pulsars PSRs J119-6127 and J1814-1744 have been discovered [25]. These pulsars with periods 0.407 s and 3.98 s, have magnetic fields $B = 4.1 \cdot 10^{13}$ Gs and $B = 5.5 \cdot 10^{13}$ Gs, and characteristic ages $\tau = 1.6 \cdot 10^3$ years and $\tau = 8.5 \cdot 10^4$ years respectively. In these two pulsars only magnetic fields are unusually high but other characteristics are normal, with the second period on the edge of the distribution. In two subsequently discovered PSRs J1847-0130 and J1718-37184 magnetic fields are even higher, and all characteristics are similar to the "magnetars". These pulsars have periods 6.7 s and 3.4 s, magnetic fields $B = 0.94 \cdot 10^{14}$ Gs and $B = 0.74 \cdot 10^{14}$ Gs, respectively, and characteristic ages $\tau = 8.3 \cdot 10^4$ years is measured only for the first pulsar [71, 72]. We may expect farther discoveries of radiopulsars with large periods and high magnetic fields, like prescribed to "magnetars" in AXP and SGR. These discoveries create additional doubts to the "magnetar" model of SGR and AXP.

9 Conclusions

1. Magnetic fields of radiopulsars are in good correspondence with theoretical estimations.
2. RP and LMXB have small magnetic fields, which very probably had been decreased by damping or screening during accretion stage.
3. Contradiction between high B_{cycl} and other observational estimations of B in the LMXB Her X-1 may be removed in the model of relativistic dipole mechanism of the formation of a hard spectral feature by strongly

anisotropic relativistic electrons, leading to conventional value of $B \approx 5 \times 10^{10}$ Gs.

4. Very high magnetic fields in magnetar model of SGR needs farther confirmation and investigation.

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